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Title: Broadband Time-Frequency Analysis Using a Multicomputer
Author: Mr. John Saunders
Mercury Computer Systems, Inc.
199 Riverneck Road, Chelmsford, MA 01824
978-967-1704/FAX 978-256-8596; jisaunde@mc.com
Citizenship: USA
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Embedded Computing for Global Sensors and Information Dominance

Time-frequency analysis techniques are used to produce a plot of a signal's power spectrum as a function of time. The most well-known time-frequency representation is the spectrogram. Although relatively simple to compute, it suffers from having a significant limitation in that it cannot offer good time or frequency resolution simultaneously. To overcome this weakness, many other representations have been developed that provide combined high resolution over time and frequency. The Wigner-Ville distribution, the scalogram, and the discrete Gabor transform are among the most well-known of these methods. Due to specific shortcomings with regard to these distributions for multi-component signals, and for certain mathematical concerns such as shift invariance and time and frequency marginal conditions, several classes of representations have been developed which effectively address specific signal types. Examples of these categories are Cohen's class, the affine class, and the signal adaptive expansions based upon the Matching Pursuit method. The goals of any of these specific methods are to minimize cross-term interference, provide good time and frequency resolution, and provide a good model for the signal of interest.

In the past, time-frequency analysis techniques have seen limited use on high-sample rate data streams. Although these methods are effective at capturing the evolution of the instantaneous frequency of non-stationary, transient and time-varying signals, the associated computational complexity has been high. As such, the application of such methods has been limited to analysis of relatively low-frequency phenomena. Examples of the types of applications generally include acoustic signals, underwater mammalian and other biological signal analysis, electro encephalograph (EEG) potentials, sonar and underwater acoustics, seismic monitoring, and fault detection and analysis of rotating machinery.

By porting these time-frequency algorithms onto a multicomputer, it becomes possible to accommodate wide-band, high-sample rate data streams. The benefit is that highly dynamic and transient phenomena within the radio spectrum can be detected, measured and identified. Several types of applications now become amenable to detailed time-frequency analysis. Examples might be spectrum compliance monitoring, modeling of time-varying channels for multiple access spread spectrum, detection of exotic waveforms buried in noise, transient signal detection, classification of signal modulation types, improved source direction of arrival (DOA) estimation performance through spatial time-frequency analysis, and interference and jammer excision.

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A multicomputer-based solution is an ideal fit to handle the large processing requirement associated with high-sample rates and high-computational complexity. The processing load can be distributed across multiple compute nodes and the data sets can be constructed to ensure efficient movement of data among the nodes. The system can be easily scaled and reconfigured to serve changing analysis requirements.

Mercury has developed a demonstration multicomputer system implementing a selection of these high-performance time-frequency analysis algorithms running in real time. The system is based on PowerPC® G4 processor with AltiVec™ technology interconnected by the RACE++® high-bandwidth switch fabric architecture. A set of powerful software tools has been utilized to implement several of these algorithms. Using MATLAB® as a starting point, the total development time to port these algorithms onto the multicomputer was quite reasonable. The demonstration, rather than including a short snippet of an interesting signal as seen in most of the literature, processes longer duration waveforms from actual radio equipment.

Abstract

Agenda

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Time Frequency Analysis for Single Channel Applications

John Saunders
Mercury Computer Systems, Inc.

High Performance Embedded Computing (HPEC) Conference
September 30, 2004

The Ultimate Performance Machine

Project Description

Implementation/Demonstration Goals

- Choose a selection of compute-intensive signal processing algorithms for demonstration on a real-time multicomputer system
- Some algorithms address problems in signal intercept or passive/active radar applications
- Follow progress of an interesting series of works performed at Naval Postgraduate School [2] (under Prof M. Fargues and former Prof R. Hippenstiel); also follow Time-Frequency toolbox [6].
  - Spectral Correlation Receiver based upon FFT Accumulation Method
  - Continuous Wavelet Transform (Scalogram)
  - Discrete Wigner-Ville Distribution with a selected set of interference-reducing kernels
  - Parallel Filter Bank and Higher Order Statistics detection
    - -- Third order cumulant detector/estimator

Project Description

Demonstration System

- Common thread with all algorithms is a high-computational load distributed over multiple nodes to achieve real-time performance.
- Generally, a demonstration of these techniques runs on a single processor system and involves a fixed signal segment and a waiting period before presentation of results.
- Our contribution is to show these algorithms running in a “dynamic spectrum analyzer” mode with streaming input signal data.
- Near real-time graphic software written to display mesh and image plots. In addition, goal is to produce real-time contour plots.
- Show ease of implementation of using scientific algorithm library (SAL) library calls.

Time Frequency Representation (TFR) Overview

- **TFRs are powerful tools to analyze, characterize, and classify dynamic signals existing in non-stationary conditions.**
- **Certain characteristics such as high resolution measurement of the instantaneous frequency and energy of a signal across time are appealing to practitioners across a wide range of science and engineering disciplines.**
- **Unfortunately the holy grail of high resolution and co-existence of multiple signals and multiple signal components remains elusive.**
- **An enormous amount of research focus has gone into obtaining the desirable mathematical properties of the Wigner-Ville Distribution without its accompanying distortion properties for the above conditions.**
- **Variety of algorithms, kernels, representations, etc. available.**
- **Many approaches involve high levels of computation, especially the fixes overlaid to overcome deficiencies of a particular technique.**

Spectral Correlation

FFT Accumulation Method [4,5]

{ $x_0, x_1, x_2, \ldots, x_{4095}$ }

4096 pt complex sample vector

8 sub-blocks

256 pt FFT filter bank

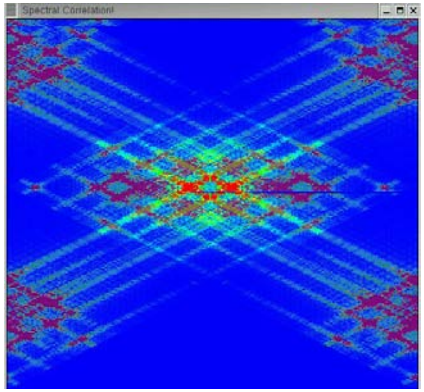
256 filters wide
8 sample deep

cross-correlate all 256 filters

8 x 65536 correlation array

reorder by cycle frequency vs. frequency

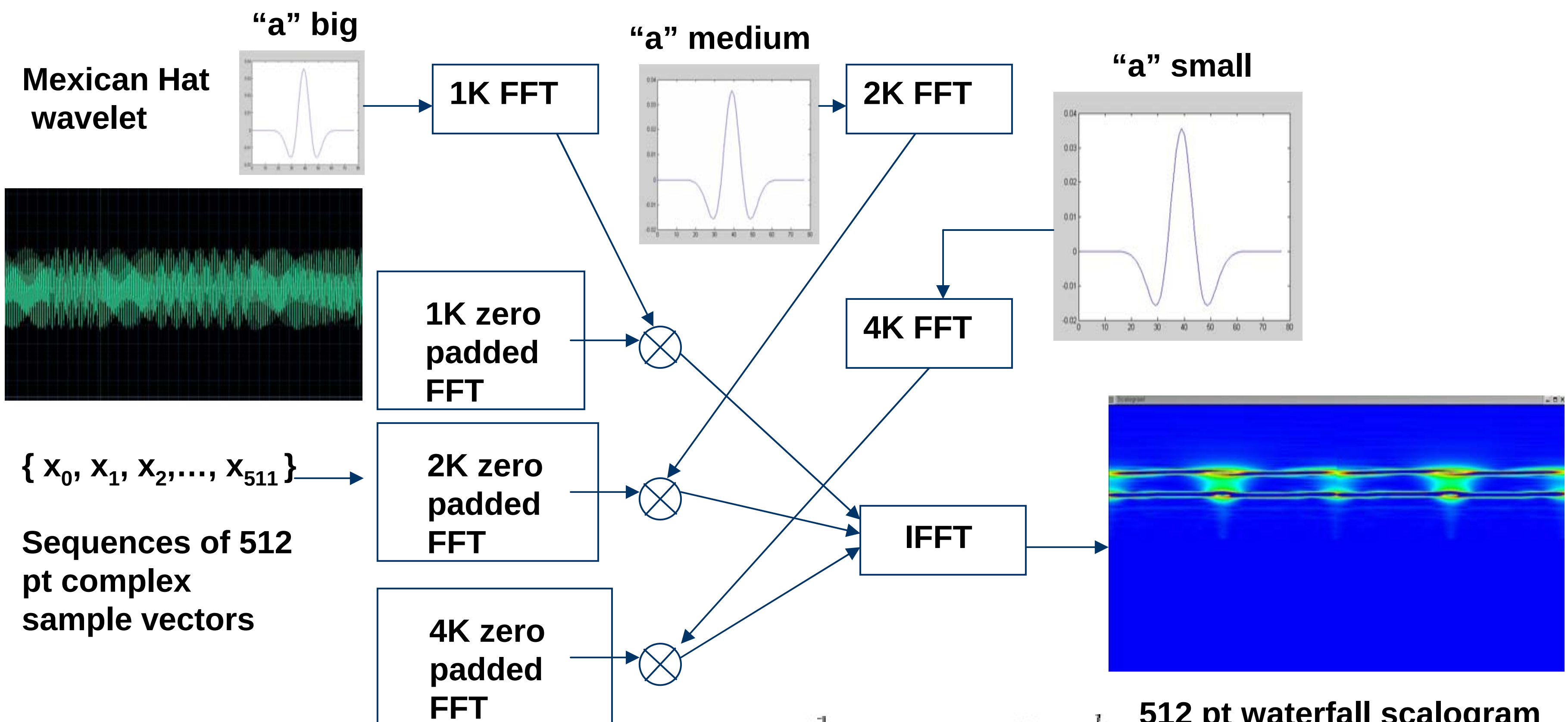
256x1024 ROS



Scalogram (CWT)

Continuous Wavelet Transform using fast convolution [6]

- As freq = 0.05 to 0.5, “a” scales from 10 to 1
- Wavelet basis is Mexican Hat function
- As a scales, the filter size scales logarithmically from 2263 to 47 pts
- Convolve with signal using either 4K, 2K, 1K, or 512 pt FFT



$$CWT[a,b] = \left(\frac{1}{\sqrt{a}}\sum_n s[n]\Psi\left(\frac{n-b}{a}\right)\right)^2$$

Wigner-Ville Distribution

Wigner-Ville Distribution [7]

- **Computed at input sample rate which drives complexity requirement**
- **Best time-frequency resolution for estimating frequencies, chirp or drift rates, event times**
- **ICF function generates interference which limits usability**
- **Satisfies many mathematical properties including energy, time and frequency marginals, instantaneous frequency and group delay**

$$WVD[m,k] = \sum_{n} s[m+n]s^{*}[m-n]e^{-j4\pi nk}$$

$\{ x_0, x_1, x_2, \ldots, x_{511} \}$

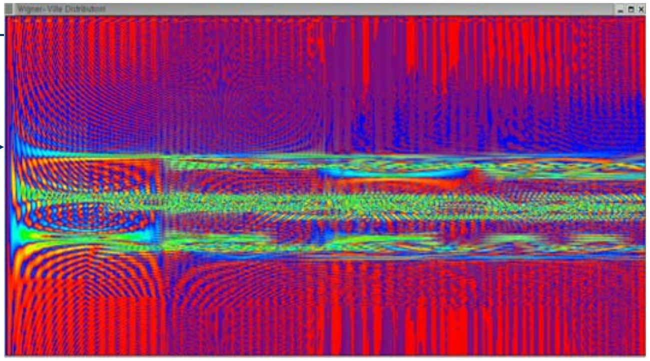
Sequences of 512 pt real or complex sample vector

Instantaneous correlation function

Hilbert Transform (if x real)

512 pt FFT

512 pt Waterfall WVD display



Smoothed Pseudo Wigner-Ville Distributio

One of many interference reduction strategies applied to WVD

- Time window the input sequence to suppress cross term interference. Little effect upon computation.
- Window in the frequency domain (convolve in time domain) which adds a significant amount to the computational complexity.
- Net effect is loss of resolution in time and frequency for suppression of interference.
- Sample rate reduction possible due to bandwidth reduction by filtering.

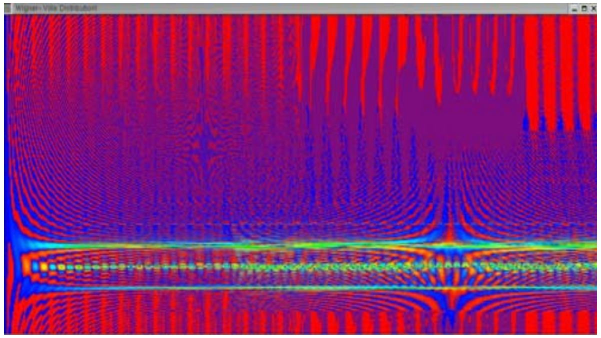
$\{ x_0, x_1, x_2, \ldots, x_{511} \}$

$$SPWVD[m,k] = \sum_n h[n]\Big(\sum_l g[l]\big(s[m+n-l]s^*[m-n-l]\big)e^{-j4\pi nk}$$

Sequences of 512 pt real or complex sample vector

Hilbert Transform (if x real) → **Instantaneous correlation function** → **Convolve w/ freq. mult by time window** → **512 pt FFT** →

512 pt Waterfall Smoothed Pseudo WVD

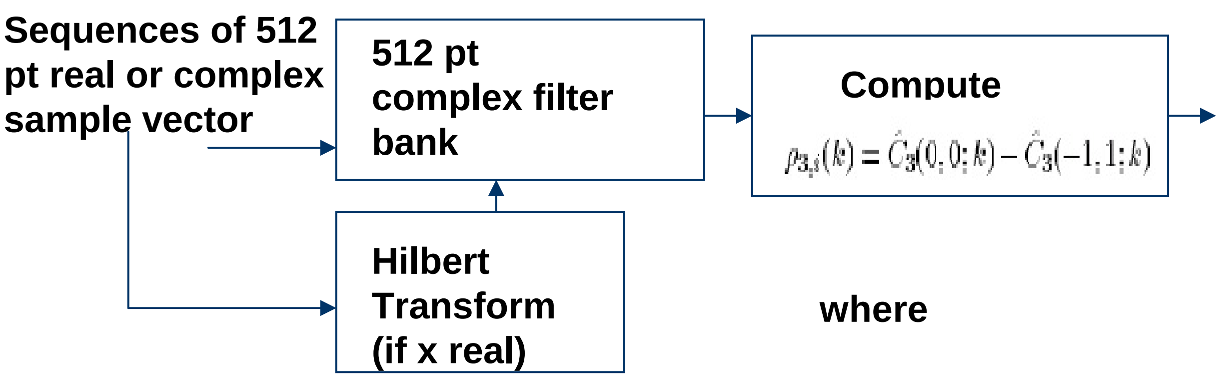


Filterbank Spectrum with Cumulant Noise Suppression

Time Frequency Detection Technique for Transients in Unknown Noise

- Purpose is to demonstrate use of cumulant calculation in a real-time signal processing application.
- Follows work of [4]Satter,F. and Salomonsson,G. “On Detection Using Filter Banks and Higher Order Statistics,” IEEE Trans. AES, Vol. 36, No. 4, Oct. 2000. Also see Taboada’s report [5].
- Computational complexity, although relatively high, is reduced by using cumulant slices along diagonal.
- Based upon difference between (0,0) lag and diagonal along (-1,1) lag.
- Suboptimal for detection of transient low SNR signals in colored noise.
- Sattar, et al., derives expression of detector in terms of Teager-Kaiser energy operator and 3rd harmonic suppression.

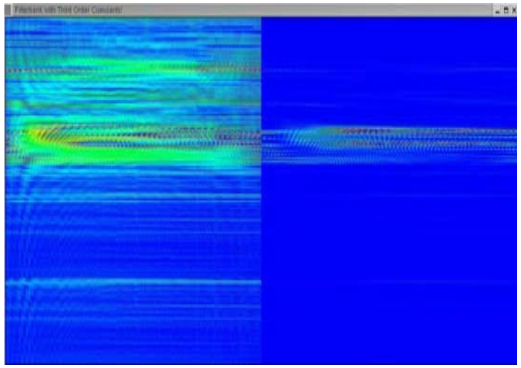
$\{ x_0, x_1, x_2, \ldots, x_{511} \}$



where

$$\hat{C}_{3,z}(l_1,l_2;k) = \sum_{n=S_1}^{S_2} z_k(n) z_k(n+l) z_k(n+l_2)$$

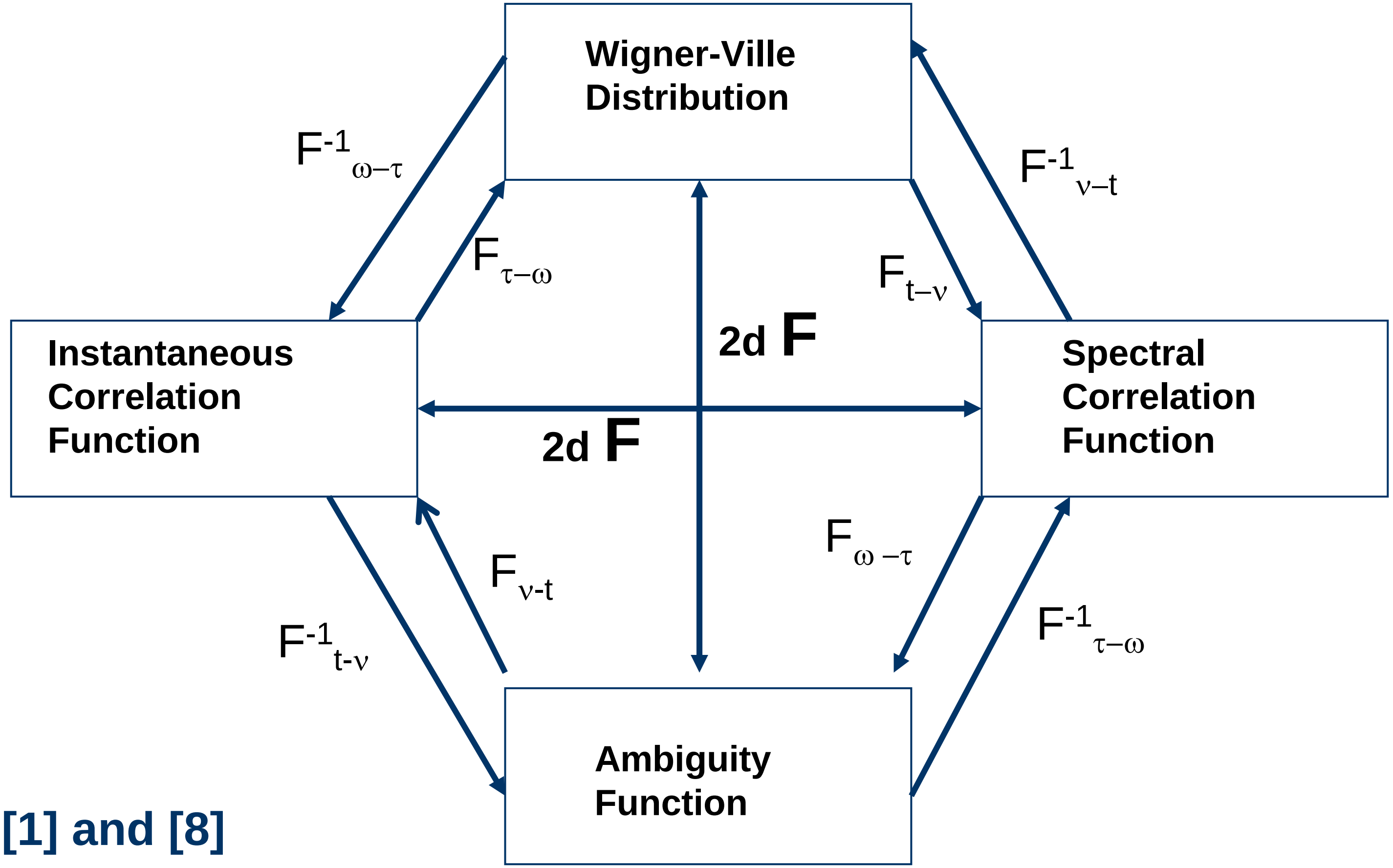
512 pt waterfall filterbank with cumulant processing



pre-filter post-filter

Demonstration Algorithms

Unifying Fourier Transform relationships between demonstration algorithms



See [1] and [8]

Time-Frequency Algorithms

Several (non-exclusive) categorizations of T-F algorithms

Order:

Linear
Quadratic
Hyperbolic
Power

Invariance property:

Time/frequency shift (Cohen's) -> kernel type
Time/scale (affine)

Signal dependence:

Signal independent
Signal adaptive

Representation / Atomic Decomposition:

Orthogonal basis functions
Non-orthogonal elementary functions

Mathematical Interpretation:

Physical: Complex exponentials as eigenfunction solutions
Statistical: no structural assumptions; "dictionary of tiled wavelets"

Algorithm:

Spectrogram
Multi-windowed spectrogram
Gabor representation
Scalogram (CWT)
Discrete Wavelet Transform
Wigner-Ville Distribution
Pseudo Wigner-Ville Distribution
Smoothed Pseudo Wigner-Ville
Choi-Williams
Cone-shaped
Rihaczek
Margeneau-Hill
Page
Born-Jordan
Reassignment techniques
I/0 kernel
Radially Gaussian Kernel
Adaptive Gabor Expansion
Adaptive chirplet Decomposition
Matching Pursuit
Basis Pursuit

Qualifications on Performance Data

- No attempt was made to lower sample rate on smoothed pseudo Wigner-Ville Distribution as made possible by filtering operations.
- No attempt has been made to optimize performance with respect to algorithmic breakdown beyond a top level.
- Example: WVD should be real, therefore could compute 2 FFT at once using odd and even input symmetries.
- No attempt has been made at optimizing performance with respect to machine and system architecture, i.e., stripmining.
- Example: Segment data blocks in consideration of processor L1 cache size to achieve fast throughput. Re-use of most recently used data segments.
- Display update rate limited by trying to get 512 KByte images through Ethernet pipe and router.

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Single Processor Measurements

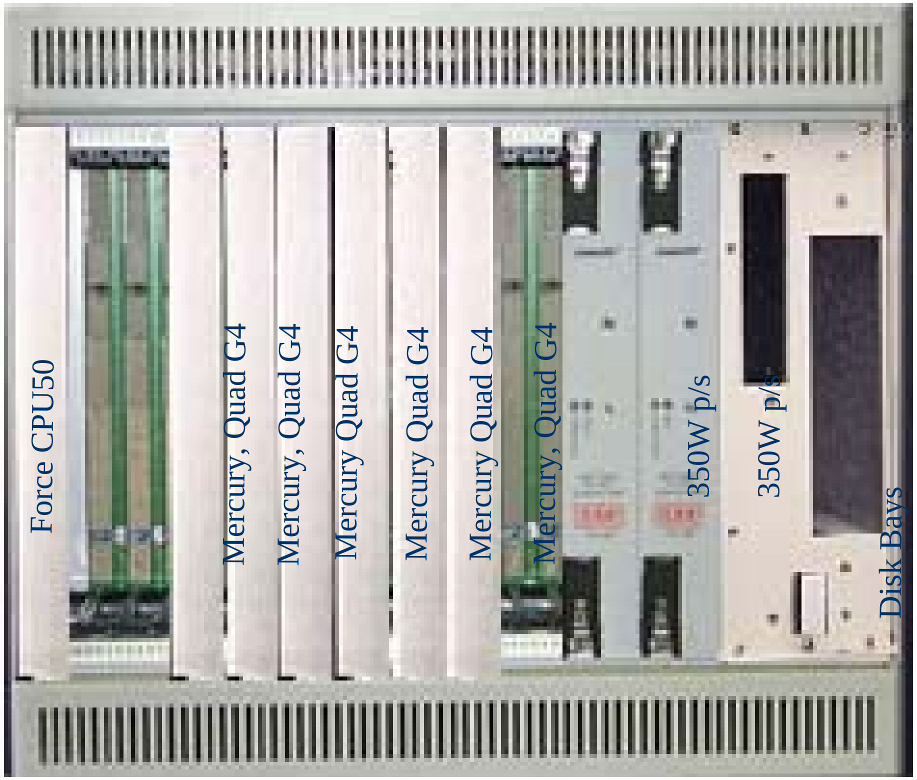
- WVD: 29 msec per 512 samples
- PWVD: 29 msec per 512 samples
- SPWVD: 650 msec per 512 samples
- Spectral Correlation: 33 msec for block of 4096 samples
- HOS filter bank: 732 msec for block of 512 samples
- Scalogram: 102 msec for block of 512 samples

Exercise:

As hypothetical example, using 64 kHz sample rate, 512 samples are collected in 8 milliseconds, 4096 samples are collected in 64 milliseconds.

Algorithm	Number processors
Spectral correlation	1
WVD	5
Scalogram	12
SPWVD	
HOS filterbank	large

Lab Development System



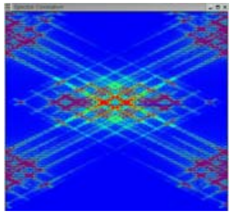
- 1X Force CPU50, 333MHz SPARC
- 6x Mercury, MCJ6 with 4x G4 7400@400MHz, with 64Mbyte RAM each
- Total of 76 Gflops peak processing
- Total of 152Gops peak 16Bit
- Dual RACE++
- Total bisection bandwidth of 1 Gbyte/sec

Demo System Configuration

Ethernet

Graphical Display PC

(Linux / Windows)



512x512 image

Mercury Compute Nodes

PAS™ over RACE++™

CN CN . . . CN

Host Processor

PAS™ over VME

Data Files

Software Tools Used

Mercury SAL™ (Scientific Application Library)

Mercury PAS™ (Parallel Acceleration System)

SDML (Simple Direct Media Layer)

SGE (SDML Graphics Extension)

SDL Draw

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Selected References

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7. Qian, S., “Introduction to Time-Frequency and Wavelet Transforms,” Prentice Hall PTR, Upper Saddle River, NJ, 2002.
8. Debnath,L, ed., “Wavelet Transforms and Time-Frequency Signal Analysis,” Birkhauser Boston, New York, NY, 2001.

Poster

Agenda

Time Frequency Analysis for Single Channel Applications

John Saunders
Mercury Computer Systems, Inc.

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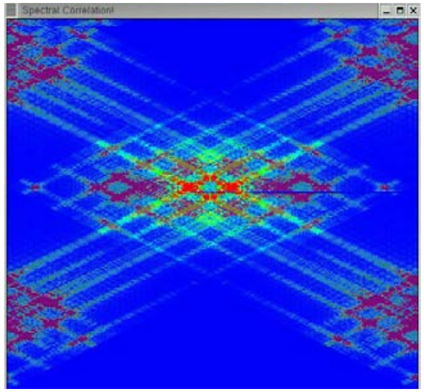
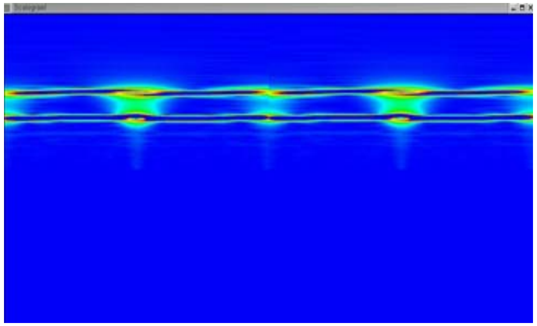
“Waterfall Displays”

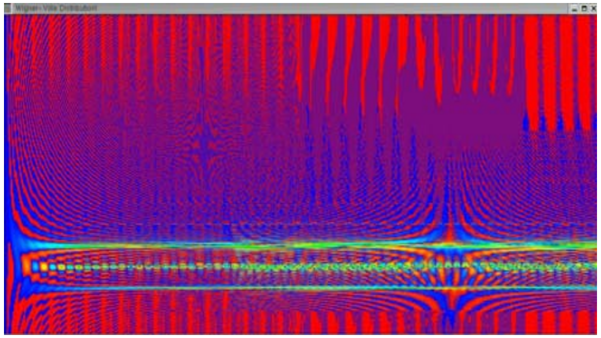
Spectral Correlation



CWT Scalogram



Smoothed Pseudo Wigner-Ville Distribution



Filter Bank with Cumulant Noise Suppression